Specification Amendments

[0032] Figure 3 is a diagram of a system for measuring optical scattering characteristics in accordance with one embodiment of the present invention. A first frequency generator 52 provides a frequency chirped signal in accordance with Figure 2. The signal is amplified by an amplifier 80 and controls the output amplitude of a laser 50. In alternative embodiments the output of the laser can be directed to an external modulator that is driven by the first signal. The output of laser 50 is a laser excitation signal. A low power laser excitation signal can be used to decrease nonlinear backscattered radiation responses. For example, a power of less than 500mW allows for use of a 1541 nm laser source while reducing nonlinear response. Alternatively, a higher power laser excitation signal could be reduced to less than 500mW by an external modulator or other optical device. The amplitude modulated light is directed to an optical target 75. In one embodiment, an optical fiber 74 is used to direct the amplitude modulated light to the optical target 75, through entrance 72 and exit 76. In one embodiment, an optical fiber is the optical target. The optical fiber can be multi-mode fiber or single-mode fiber. A portion of the backscattered light from the optical target traverses filter 90 and is received by a avalanche photodiode 58. The filter 90 determines the type of backscattered radiation received by the avalanche photodiode 58. For example, the filter 90 may allow only Rayleigh radiation or Stokes radiation depending on the wavelengths that the filter 90 transfers and blocks.

[0035] An expression for the instantaneous frequency of the chirp is:

$$f(t) = f_0 + \gamma \mathrm{mod}(t, \tau) \qquad \text{Eqn. 1}$$

where f_0 is the minimum frequency, γ is the chirp rate, and τ is the chirp period. The laser's output power waveform then has the form:

$$\begin{aligned} P(t) &= 0, t < 0 \\ P(t) &= P_0\{1 - m\sin^2[\varphi(t)/2]\}, 0 \le t \end{aligned} \qquad \text{Eqn. 2}$$

with

$$\varphi(t) = 2\pi \int f(t)dt \qquad \text{Eqn. 3}$$

where $\varphi(t)$ is the phase of the waveform. The excitation shown in Eqn. 2 can be rewritten as:

$$P(t) = P_0\{1 - \tfrac{1}{2}m + \tfrac{1}{2}m\cos[\varphi(t)]\}\,. \qquad \text{Eqn. 4}$$

The time span of the dashed regions in Figure 4 is just $\frac{2L}{c}$. In one embodiment, only data from outside the dashed regions is considered for determining optical backscattering characteristics. In that embodiment, data is available if $\frac{2L}{c} < \tau$.

[0036] Eqn. 4 shows that the intensity modulation of the backscattered radiation received from the optical target will have both a DC and an AC component. The AC component of the modulation of the received backscattered radiation intensity as a function of time from a fiber of length, L, and absorption coefficient, $\alpha(\ell)$, can be expressed as an integral over the length of the fiber, after an initial transient period of one round trip time on the fiber, 2L/c:

$$r(t) = \tfrac{1}{2}mP_0\int_0^L \exp\left[-2\int_0^\ell \alpha(\ell')\,d\ell'\right]\cos[\varphi(t - \tfrac{2\ell}{c})]\,\sigma(\ell)\,d\ell \qquad \text{Eqn. 5}$$

for $t > \frac{2L}{c}$

where $\sigma(l)$ measures the returned strength, from position l, of the backscattered signal that is trapped in the fiber and c is the speed of light in the fiber. In one embodiment, $\alpha(\ell)$ is assumed to be a constant, independent of l, so that the interior integral of Eqn. 5 is equal to αl. With that assumption the complex return, **R**(t) can be defined as

$$\mathbf{R}(t) = \tfrac{1}{2}mP_0\int_0^L e^{-2\alpha\ell}e^{i\varphi(t-\frac{2\ell}{c})}\sigma(\ell)\,d\ell \qquad \text{Eqn. 6}$$

so that:

$$r(t) = \mathrm{Re}[\mathbf{R}(t)]\,. \qquad \text{Eqn. 7}$$

[0041] We are only able to collect data for positive frequencies, $f(t)$, so we only have experimental data for positive values of $k(t)$. However, if we examine Eqn. 11 for $\hat{M}(k)$, we see that if the condition

$$\pi\gamma(2L/c)^2 \ll 1 \qquad \text{Eqn. 15}$$

is met, then $\hat{M}(-k) \approx \hat{M}^*(k)$, where * indicates complex conjugation. Thus, $\hat{M}(k)$ may be extended by this process, which we call bookmatching, to include negative k. This will permit us to set $\langle k \rangle = 0$ in Eqn. 14. The remaining terms will then vary much more slowly than the sinc function. If we also choose $k_1 = 0$, Eqn. 14 takes the approximate form

$$\begin{aligned}\tilde{M}\left(\hat{l},k_2\right) &= \int_{-k_2}^{k_2} \hat{M}(k) e^{i2\pi k\hat{l}}\,dk \\ &\approx 2Ak_2 \int_0^L e^{-2\alpha\ell}\sigma(\ell)\,\mathrm{sinc}\left[2k_2\left(\hat{l}-\ell\right)\right]d\ell \qquad \text{Eqn. 16} \\ &\approx Ae^{-2\alpha\hat{l}}\sigma\left(\hat{l}\right), \quad 0 \le \hat{l} \le L\end{aligned}$$

where we have approximated $e^{i\pi\gamma\left(\frac{2\ell}{c}\right)^2} \approx 1$ and $2k_2\,\mathrm{sinc}\left[2k_2\left(\hat{l}-\ell\right)\right] \approx \delta\left(\hat{l}-\ell\right)$. The first approximation becomes exact when $\gamma = 0$.

[0052] A second frequency generator 54 is phase-locked to the first frequency generator 52 such that a second signal is produced that has a fixed frequency offset from the first signal. In one embodiment that fixed frequency offset is 10 kilohertz. The first mixer 84 receives the amplified detected backscattered signal as one input and the second signal as another. It outputs a first mixed signal. The second mixer 82 receives the amplified detected reference signal, or first signal copy, as one input and the second signal as another. It outputs a second mixed signal. The first and second mixed signals are coupled to a low pass filter 60 to remove high frequency components. The mixed signals are then digitized by analog-to-digital converters 62. The digitized signals are fed to fast fourier circuits 64 to be transformed to the frequency domain. In an alternate embodiment, the fast fourier operation could be accomplished in software rather than

hardware. The offset frequency domain signal, 10 kilohertz in this embodiment, of each of the digitized frequency domain signals is captured in the peak capture circuit 66. The offset frequency contains the modulation information. A divider circuit 68 divides the captured offset frequency of the first mixed signal by the captured offset frequency of the second mixed signal and provides the result to a processor 86. In an alternate embodiment, the captured offset frequency of the first mixed signal can be divided by the captured offset frequency of the second mixed signal in software. The processor 86 determines characteristics of the optical fiber 74 from the received signals as expressed in the divider output. <u>In another embodiment, a second detector 58 is positioned to receive radiation backscattered by the optical fiber 74 in response to the coupled excitation signal and sensitive to a different spectrum of backscattered radiation frequencies than the first detector.</u>